Carrier lifetimes in ion-damaged GaAs

M. B. Johnson[a] and T. C. McGill
California Institute of Technology, Pasadena, California 91125

N. G. Paulter[b]
Electronics Research Group, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 5 December 1988; accepted for publication 4 April 1989)

Photoluminescence excitation correlation spectroscopy has been used to measure the dependence of carrier lifetime on the H^+ ion implantation dose in GaAs. For doses greater than 1×10^{12} cm^{-2} the carrier lifetime is inversely proportional to the ion dose. The minimum lifetime measured was 0.6 ± 0.2 ps for a dose of 1×10^{14} cm^{-2}. Most important, there is no sign of saturation of carrier lifetime with ion dose down to this lifetime, thus still shorter lifetimes should be achievable with increased ion dose.

There is much interest in the generation of ultrashort electrical pulses. These ultrashort electrical pulses are generated on high-frequency waveguide structures using photoactivated switches called photoconductive circuit elements (PCEs) or Auston switches.[1] The same PCEs can also be used to sample ultrashort electrical pulses. Thus, these pulses can be used to measure ultrafast electrical transients of high-speed devices or high-frequency electrical properties of materials. A typical PCE consists of a gap between two metal conducting electrodes connected by a photosensitive insulating semiconductor substrate. The speed of the PCE is determined by the speed of the laser pulse, the geometry of the PCE, the characteristics of the waveguide, and the carrier lifetime of the semiconductor. The short carrier lifetime materials required for PCEs are produced by damaging the crystalline structure of a semiconductor by using ion implantation, or by growing intentionally poor electrical quality material. In the work reported in this letter we are interested in materials for PCEs made by using ion implantation damage. For GaAs substrates, ion implantation with 2 MeV H^+ or 200–300 keV H^+ has been successfully used.[2–4] For silicon-on-sapphire substrates a particularly successful procedure uses implantation of O^+ at 200 and 100 keV.[5]

It is interesting to compare the response speed of a PCE to the lifetimes of carriers in the PCE substrate. This has been done for PCEs on silicon-on-sapphire implanted with 200 and 100 keV O^+ ions by Doany *et al.*[6,7] The response speeds of the PCE were measured using a cross-correlation measurement[5] and the carrier lifetimes were measured using time-resolved reflectivity to measure the decay of the charge in the Si layer.[6] In that work, it was found that the carrier lifetime decreases inversely with the implant dose up to a critical ion dose of 10^{14} cm^{-2}. Above this dose, the lifetime did not reduce further but remained at 600 fs. This limit is thought to be due to amorphization or a saturation of the effective trap density in crystalline Si.[6] This lifetime limit corresponds to the 0.6 ps electrical pulses produced by Ketchen *et al.* using a sliding contact switch,[5] which suggests that it is the carrier lifetime that limits the speed of the PCEs. These results imply that the 0.6-ps-wide electrical pulse is the shortest pulse that can be produced using PCEs on implanted silicon-on-sapphire.[6]

In the work reported here, PCEs on ion-implanted GaAs are investigated. The response of the PCE is measured using a cross-correlation measurement, and the lifetime of the ion-damaged material is measured using photoluminescence excitation correlation spectroscopy (PECS).[8] PECS is a pulse-probe correlation technique which measures the decay time for capture-dominated samples. We looked at samples of GaAs that were undamaged, and samples damaged with 200 keV H^+ ions at doses in the range of 1×10^{11}–3×10^{14} cm^{-2}. For doses larger than about 6×10^{12} cm^{-2}, the lifetime versus dose has slope of -1, implying that the defect density is proportional to the dose, as expected. The smallest lifetime measured was 0.6 ± 0.2 ps corresponding to a dose of 1×10^{14} cm^{-2}. Experimentally, no lifetime saturation with ion dose is observed up to a dose of 1×10^{14} cm^{-2}; therefore, still lower carrier lifetimes should be attainable. The PCE cross-correlation measurements show a decrease in the width of the cross-correlation peak with dose; however, the width decays less quickly with dose than the carrier lifetime, suggesting that other effects in addition to the lifetime govern the PCE speed. The optimum PCE uses an ion dose of 6×10^{13} cm^{-2} which yields a pulse with a full width at half maximum (FWHM) of 9 ps.

The samples used in the work reported here were fabricated on (100) semi-insulating (SI) liquid-encapsulated Czochralski (LEC) GaAs substrates. The PECS lifetime studies were made on the same samples that the PCEs were fabricated, but on an adjacent area that was ion implanted but not metallized. The PCE structure is integrated onto a 300 GHz coplanar waveguide structure. Details of the structure and its fabrication are in Ref. 4. The conductors are Au:Ge:Ni alloy contacts on the GaAs substrate. Following the anneal to form ohmic contacts, the entire structure is ion damaged with 200 keV H^+ ions using a Varian ion implanter. Total doses of 1, 3, and 6×10^{12}; 1, 3, and 6×10^{13}; and 1 and 3×10^{14} were implanted. Two different implantation current densities were used to achieve this range of implants. The current density values used for implant doses of 6×10^{12} cm^{-2} and higher doses were 3.7×10^{-8} A/cm^2, while for the lower doses the current density was about $5\times$ smaller. During the implant the sample is on a steel block, which is cooled

[a] Present address: IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598.

[b] Present address: National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80303.

to 8 °C to reduce the effects of heating caused by the ion beam.

The PECS apparatus is discussed in detail in Ref. 8. A colliding-pulse mode-locked (CPM) ring dye laser is used to generate pulses of 200 fs full width at half maximum (FWHM) with a repetition rate of 120 MHz. The pulse wavelength is centered near 6200 Å with a spectral width of about 20 Å FWHM. A single beam is separated into two pulse trains using an interferometer which allows the pulse trains to be delayed with respect to each other by a variable delay time γ, and separately chopped at frequencies $f_1 = 1603$ Hz and $f_2 = 2005$ Hz. The two trains are recombined and focused down to a 25-μm-diam spot on the sample. Typically, the laser pump power was 1–2 mW per unchopped beam at the sample, or 8–16 pJ per pulse. The photoluminescence (PL) from the sample is spectrally resolved using a double-pass spectrometer and detected using a GaAs photomultiplier tube (PMT). The PMT signal is amplified and detected using a lock-in amplifier tuned to either the fundamental frequency f_1 or the difference frequency $f_{\rm diff} = f_2 - f_1$. A cold-finger dewar is run with liquid nitrogen and empty to achieve temperatures of about 77 and 300 K, respectively.

The apparatus and procedures used to make the PCE cross-correlation measurements are described in detail in Ref. 4. In this measurement a CPM laser pulse incident on a biased PCE generates a short electrical pulse on a waveguide. A second laser pulse delayed in time with respect to the first by a variable delay γ is incident on an adjacent unbiased PCE. The current from this second PCE samples the voltage pulse on the waveguide at this position. Thus, by varying the delay time, the current signal from the second PCE measures the cross correlation of the responses of the PCEs.

The PL intensity was found to be independent of both analysis position and laser exposure time. Delay-time scans were made for the samples at temperatures of 77 and 300 K at the wavelength corresponding to the maximum of the near band-to-band PL peak, 8260 and 8600 Å, respectively. Figure 1 shows delay-time scans at 77 K for selected samples with different doses. The results for 300 K are similar. The scans in Fig. 1 show a coherence peak at zero delay and symmetric decay about this peak. The coherence peak is due to the optical interference of the two exciting pulses when they directly overlap and is not of interest in this work. Each scan shows linear decay over at least one decade. The tails for ion dose of 10^{11} cm^{-2} are the background noise. The semilogarithmic plots show an exponential decay with a single time constant that corresponds to the lifetime of the electrons and holes. One lifetime is expected because the size of the carrier density is larger than the density of traps, which requires the population of n and p to remain close to one another as they decay. For the delay-time scans shown in Fig. 1, the lifetimes are 240 ± 80, 107 ± 10, 38 ± 2, and 7 ± 2 ps for doses of 0, 10^{11}, 10^{12}, and 10^{13} cm^{-2}, respectively. These lifetimes are the average of several delay-time scans and their errors are the standard deviation of this average. The smallest lifetime measured was 0.6 ± 0.2 ps at a temperature of 77 K and a dose of 1×10^{14} cm^{-2}. For this dose the lifetime was only measured at 77 K because the detected PL signal at 300 K is weaker than that at 77 K, so that there was too much noise at 300 K to make a measurement. Lifetime measurements of more heavily ion-damaged samples were not made because of too much noise in their delay-time data.

PCE cross-correlation scans for samples were made at 300 K. Figure 2 shows the PCE cross-correlation scans with samples for ion doses of 10^{13} and 10^{14} cm^{-2}. The lower delay-time sides of the cross-correlation peak for both scans are smooth and monotonic. However, on the high delay-time side of the peak there are small peaks due to pulse reflections. To compare the PCE responses for different doses, the half width at half maximum (HWHM) on the lower delay-time side is used because this is not affected by these reflections. The HWHM of the cross-correlation peaks shown are 13

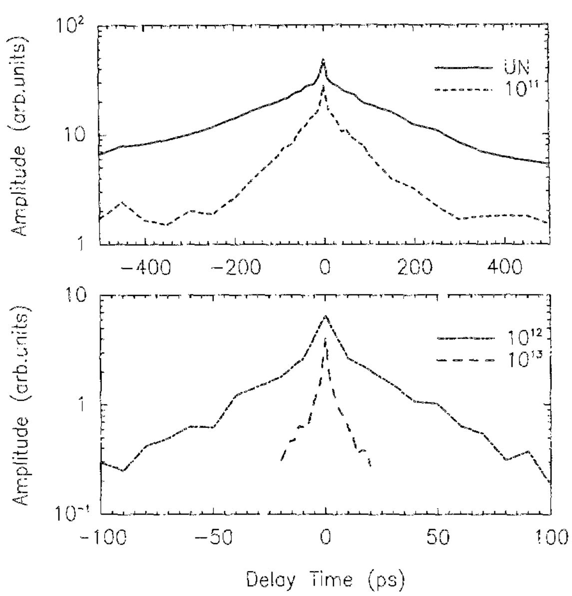

FIG. 1. Semilogarithmic plot of the variation of the difference frequency luminescence signal with delay time γ. The plots are for a sample temperature of 77 K and a wavelength of 8260 Å. Plots for ion doses of 0 (undamaged), 10^{11}, 10^{12}, and 10^{13} cm^{-2} are shown.

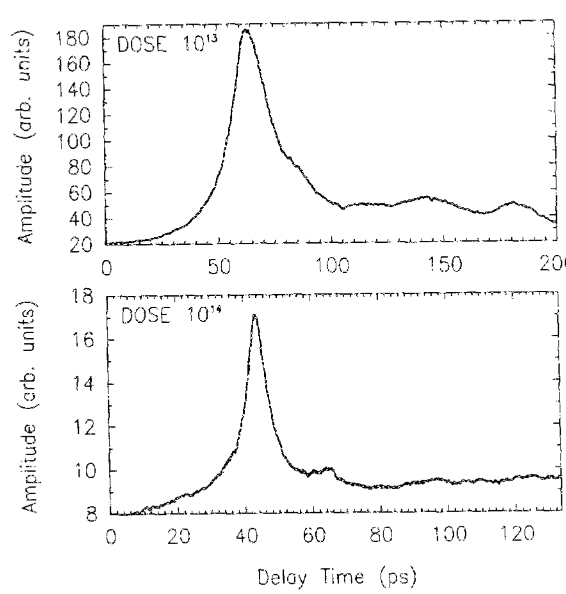

FIG. 2. Plots of the PCE cross-correlation signal. The two plots show scans for ion doses of 10^{13} and 10^{14} cm^{-2}, as labeled.

and 4 ps for doses of 10^{13} and 10^{14} cm^{-2}, respectively.

Figure 3 shows two plots. Plot (a) shows the carrier lifetime versus ion dose at 77 and 300 K, while plot (b) shows the PCE cross-correlation HWHM versus dose at room temperature. On both plots a slope of -1 representing an inverse dependence with dose is shown for reference. In plot (a) little difference is seen between the carrier lifetimes at 77 and 300 K. The notch at dose 3×10^{12} cm^{-2} is due to a change in the ion current used for low and high ion implantation doses. This indicates that annealing out of defects occurs due to the beam heating of the substrate. The slope for doses greater than 6×10^{12} cm^{-2} is -1 indicating that the lifetime is inversely proportional to dose, as expected. In plot (b) showing the PCEs speed at room temperature the same notch at a dose of 3×10^{12} cm^{-2} present in plot (a) is observed. Above dose 3×10^{12} cm^{-2} the slope is less than -1 indicating that the lifetime reduction due to damage is not the only factor governing the PCEs speed.

The effect of ion bombardment of GaAs with 200 keV H^+ ions is modeled using TRIM,[9] which is a Monte Carlo model that simulates the ions' collisions as they penetrate the surface of the substrate. The simulation keeps track of the number and position of the vacancies produced by the collisions in the cascade.[9] Along with these vacancies, the collision cascades will introduce other trapping defects into the crystal. It is reasonable that the distribution of trapping defects is similar to the vacancy distribution. The peak of the vacancy distribution is at 1.5 μm which is much deeper than the 0.25 μm depth probed by the PL measurements. In the top 0.25 μm, the average vacancy density is 2.5×10^{18} cm^{-3}, which represents an average of about one vacancy per ten thousand atomic sites. Such a density suggests this top 0.25 μm of the damaged material is far below the amorphization limit. In the case of the implantation of 200 keV O^+ in silicon-on-sapphire used in Ref. 6, TRIM indicates that there is a higher average density of vacancies in the 0.5 μm Si layer. For a dose of 3×10^{14} cm^{-2}, the average vacancy density is 2.4×10^{21} cm^{-3} in the Si layer, which represents an average of one vacancy in ten atomic sites. Such a density suggests the Si layer is close to the amorphization limit. Comparing the two vacancy densities, it is not surprising that the carrier lifetime of the Si layer saturates, while the carrier lifetime of the GaAs does not saturate. The fact that the lifetime of GaAs is comparable to that of the Si, although the amount of damage is much smaller suggests that the capture cross section of the dominant defects in the GaAs is much higher than the defects in the Si. Because the carrier lifetime of GaAs does not saturate before reaching the lifetime at which the Si layer saturates, shorter carrier lifetimes may be achieved with the damaged GaAs than for the damaged Si-on-sapphire.

In the work done in this letter, the shorter carrier lifetimes do not translate into PCE response times as fast as those seen by Ketchen *et al.*[5] The reason for this is suggested by the fact that the slope of the plot of response speed versus damage is greater than -1 which indicates that some effect other than carrier lifetime limits the PCE device speed. The most obvious frequency limiting effect is the capacitance of the PCEs used in this work, and thus improvements in PCE switching speed should be obtained using the sliding-contact PCE described by Ketchen *et al.*[5] Further effects that may contribute to the PCE response behavior with ion dose include problems in the ohmic contacts between the PCE conductors and the SI GaAs substrate, and the nonuniform damage density in the top 0.25 μm photosensitive layer. However, the fact remains that shorter carrier lifetimes appear achievable with the damaged GaAs than with the damaged Si in the Si-on-sapphire suggesting that similar PCE structures on the GaAs may achieve faster switching speeds.

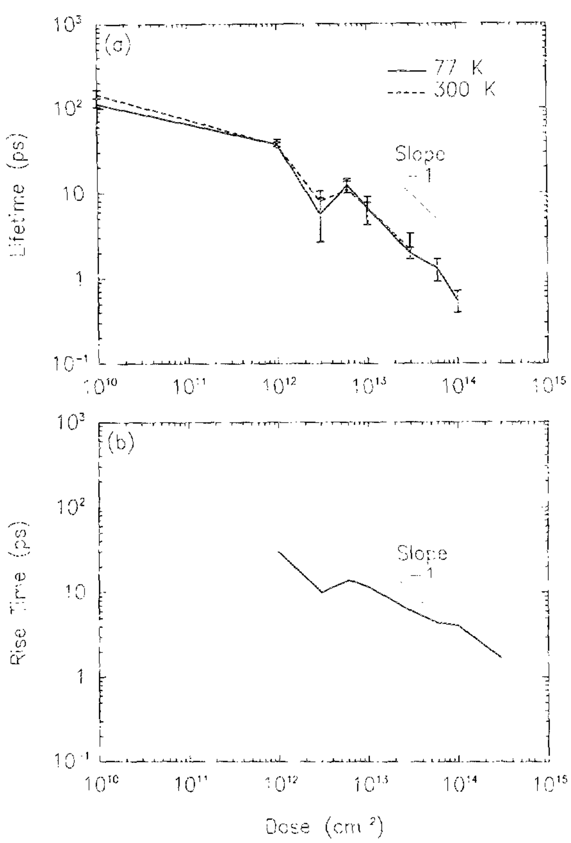

FIG. 3. (a) shows the carrier lifetime vs ion dose. The lifetimes at 77 and 300 K are shown as solid and as dashed lines, respectively. (b) shows the PCE cross-correlation half width at half maximum (HWHM) vs ion dose. The half maximum is taken as halfway between the peak and background.

The authors would like to acknowledge Al Gibbs of Los Alamos National Labs for the sample processing. One of us (M. B. J.) would like to thank Dr. A. T. Hunter of Hughes Research Laboratories for helpful discussions about this work. This work was supported in part by the Defense Advanced Research Projects Agency under contract No. N00014-84-K-0501.

[1] D. H. Auston, IEEE J. Quantum Electron. **QE-19**, 639 (1983).
[2] R. B. Hammond, N. G. Paulter, and R. S. Wagner, Appl. Phys. Lett. **45**, 289 (1984).
[3] D. H. Auston and P. R. Smith, Appl. Phys. Lett. **41**, 599 (1982).
[4] N. G. Paulter, IEEE Trans. Instrum. Meas. **IM-37**, 449 (1988).
[5] M. B. Ketchen, D. Grischkowsky, T. C. Chen, C-C. Chi, I. N. Duling III, N. J. Halas, J-M. Halbout, J. A. Kash, and G. P. Li, Appl. Phys. Lett. **48**, 751 (1986).
[6] F. E. Doany, D. Grischkowsky, and C.-C. Chi, Appl. Phys. Lett. **50**, 460 (1987).
[7] F. E. Doany and D. Grischkowsky, Appl. Phys. Lett. **52**, 36 (1988).
[8] M. B. Johnson, A. T. Hunter, and T. C. McGill, J. Appl. Phys. **63**, 2077 (1988).
[9] J. F. Ziegler, J. P. Biersack, and U. Littmark, *Stopping and Range of Ions in Solids* (Pergamon, New York, 1985).